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THE EFFECT OF A VISUAL/MOTION DISPLAY MISMATCH IN A SINGLE AXIS COMPENSATORY TRACKING TASK*

By

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Abstract

An experiment is performed to determine the effect of a performance mismatch between the visual and motion display systems on a real-time piloted aircraft simulation (usually motion displays exhibit more phase lag than visual displays). Pilots perform a compensatory roll tracking task with dynamics typical of medium jet transports. Between 0 and 10 rad/sec, visual and motion system responses are equivalent to either unity or a first order lag at 4.8 rad/sec. Pilot describing functions and error scores are calculated. Results show that the mismatch between visual and motion display systems has no significant effect; rather, it is the absence of high frequency visual and/or motion cues which significantly affects pilot performance.

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Introduction

It is possible for a pilot to "fly" a simulated aircraft which duplicates the sensations of flight without leaving the ground. The keys to such a realistic simulation are the simulator cab and computers. The simulator cab, as sketched in Figure 1, provides the pilot with the physical sensations of aircraft flight. Included are cab motions, operational instruments normally found in the aircraft being simulated, controls with the same force-feel as the simulated aircraft, TV and/or computer graphics displays of the outside visual scene, and simulation of the engine and landing gear sounds. The computers control the simulation hardware which provides these sensations to the pilot, monitor pilot responses and control commands, and use a mathematical model of the aircraft to calculate its response to the pilot commands.

The simulation of visual and motion cues for the pilot is basic to most simulations at NASA-Ames Research Center. The most commonly used visual display is a TV picture of a terrain model. A six-degree-of-freedom servo-system, under digital computer control, drives the TV camera to simulate the pilot's view out the cockpit window as if he were flying the actual aircraft. Similarly, a six-degree-of-freedom servo-system is used to move the entire simulator cab in order to give the pilot motion cues. Motion cues help the pilot control the simulated aircraft, and enhance the realism of the simulation.

The motion simulator cab has significantly greater mass than the TV camera, and consequently requires considerably more power to accelerate than the TV camera. Consequently, one often finds a difference in performance between the servo-system driving the cab motion and that driving the visual display. The frequency response of visual systems is typically unity from 0 to 20 rad/sec, while that of motion systems typically falls off in the vicinity of 6 rad/sec. The question arises as to what effect, if any, such a difference in servomechanism performance has on the simulation. Is pilot performance reduced by the conflict between displays? Would a more realistic simulation occur if the visual servomechanisms were degraded to match the motion servomechanisms? Does the pilot need and use the higher frequency information

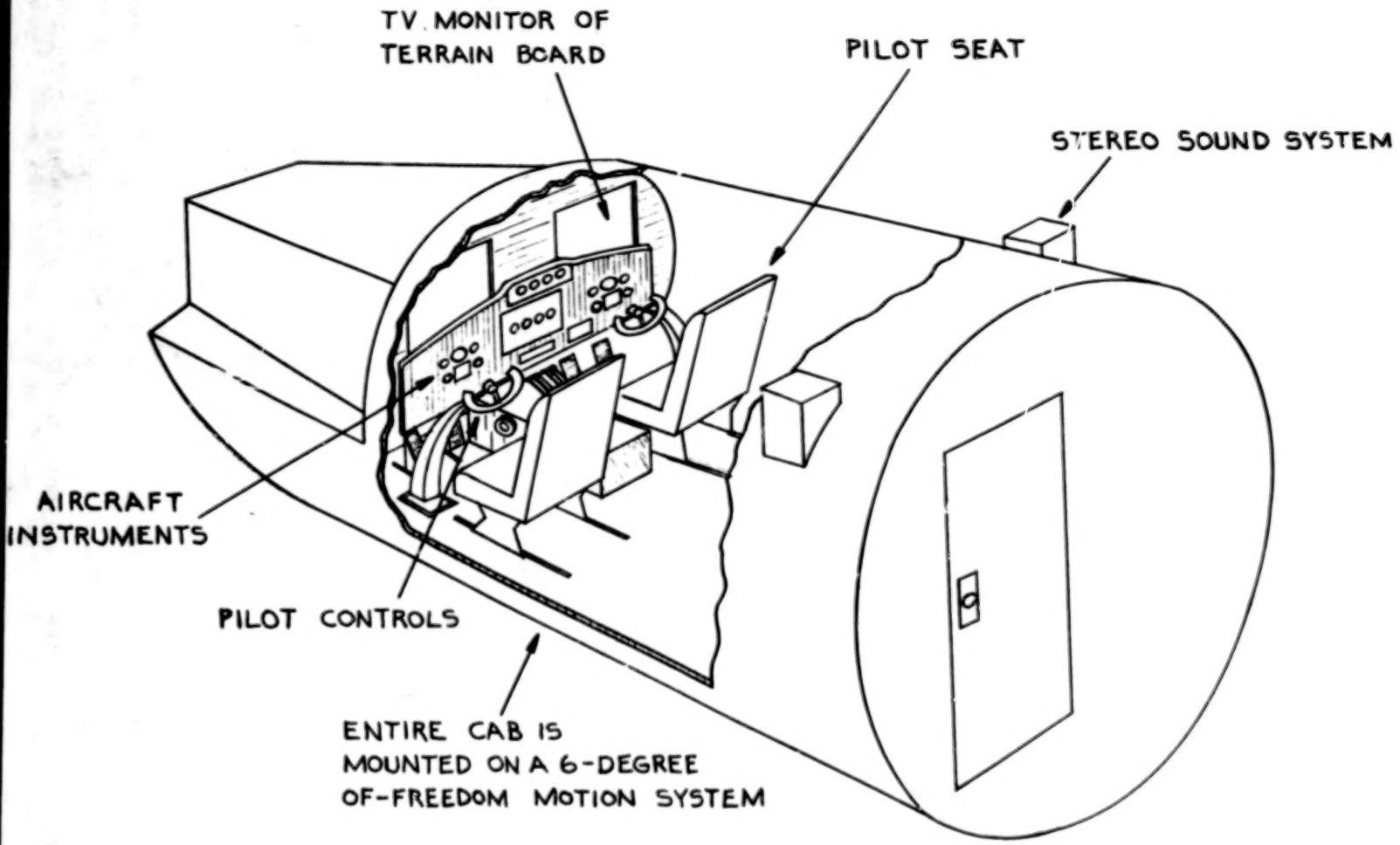


Figure 1: DIAGRAM OF SIMULATION CAB
(CUTAWAY VIEW)

present in the visual display? The purpose of the experiment reported in this paper is to take a step forward toward answering these questions.

There are three practical reasons why the answers to the above questions would be useful to aircraft simulation. It is desirable to improve the reality of a simulation so that results obtained are more applicable to and representative of actual flight. Secondly, it is useful in aircraft design to have insight into how a pilot controls an aircraft, especially in terms of what information he uses to guide his control commands. Finally, one must know what capabilities are required from a simulator in order to provide realistic aircraft simulations.

The next section of this paper outlines work already in the literature which bears on these questions. A description is then given of an experiment used to check for the effects of a difference in the performance of the visual and motion servomechanisms (the experiment uses a single-axis, compensatory, roll-tracking task). The results of the experiment are then presented and analyzed.

Literature Review

Much of the early research performed on moving-base simulators was related to a roll control task, since a major contribution to the lateral maneuverability of an aircraft is provided by its roll dynamics. The primary goals of these earlier research efforts were (1) to compare pilot performance in fixed-base and moving-base simulators to actual flight data and (2) to define and evaluate parameters for aircraft handling qualities. The methods used in these studies were measurements of pilot describing functions (pilot amplitude ratio, phase and noise versus frequency) such as those described in reference 1, subjective ratings similar to the Cooper-Harper Rating Scale (described in reference 2), and various measures of system performance (such as integral squared error).

In his experiments, Newell (reference 3) reported data which showed that pilot performance for instrument-only, fixed-base simulations was similar to that for instrument-only flight conditions. Pilot describing functions

showed lower amplitude ratios for fixed-base, instrument-only simulations and instrument-only flight conditions than for in-flight visual conditions. Newell and Smith (reference 4) verified these results and also observed that visual flight conditions and fixed-base visual simulations produced similar pilot describing functions. In addition, fixed-base visual simulations showed pilot performance which was closer to that for in-flight visual conditions than that for instrument-only conditions (either flight or fixed-base simulations). In other words, the absence or presence of a visual scene in addition to the instruments had more effect on pilot performance than the absence or presence of motion cues. It should be noted that these results were obtained in the absence of turbulence.

In 1959 Creer, et. al. (reference 5) used simulator and in-flight studies to define the effects of roll damping and roll control power on the pilot by recording pilot opinion ratings for the different parametric conditions. Based upon these pilot ratings, their results showed that there was good correlation between moving-base simulator and in-flight pilot opinions. The fixed-base simulator results agreed with moving-base simulator and in-flight conditions only for small roll accelerations. For larger roll accelerations, the moving-base simulations and actual flights produced similar data, while the fixed-base simulation led to significantly different pilot opinion ratings. Because of the results of Creer and others, which indicated that a moving-base simulator would be necessary for realistic ground-based simulation of flight, further simulator research proceeded in the direction of evaluating various motion display systems.

The methodology pursued by subsequent research efforts was to change the dynamic characteristics of the motion simulator, visual display and/or aircraft plant, and measure these effects upon pilot performance. Shirley and Young (reference 6) studied the effects of visual and/or motion cues on pilot describing functions in a roll compensatory tracking task. Their conclusions were that the effect of adding simulator motion to the visual display was to increase pilot phase lead above 3 rad/sec and to increase pilot gain between 0.1 rad/sec and 10 rad/sec. They also observed that low

stick gain or very slow plant dynamics tended to minimize the advantage of roll motion as a cue to the pilot.

Schmidt and Conrad (reference 7) used a six-degree-of-freedom simulation in their investigation of a formation flying task with various choices of aircraft dynamics. They showed that motion cues decreased the scatter of the lateral and vertical deviation error scores as compared to a fixed-base condition. The scatter of the fixed-base error scores increased as the simulated aircraft dynamics became less acceptable. They also observed that without motion cues, pilots were unable to damp out the dutch roll mode.

Recently, Junker and Replogle (reference 8) have investigated the effects of motion simulation for a large amplitude, roll control task upon pilot performance as a function of increasing plant complexity. Their data showed that simulator motion had the effect of reducing task learning time and improving tracking ability as compared to fixed-base runs. The error scores increased as plant order increased, as did the pilot effort required to maintain stable control of the plant. Differences between fixed-base and moving-base simulator error scores became more pronounced as the order of the plant increased.

A previous study closely related to the research described in this report was that of Stapleford, et. al. (reference 9), who determined separate pilot describing functions for the visual and motion display systems. Their data showed that the remnant spectrum was flat throughout the bandwidth investigated (1-20 rad/sec) with a fixed-base task producing twice as much remnant as a moving-base task, and that the error score was lower when motion cues were added to the simulation. They concluded that motion cues became more important as the need for the pilot to generate lead was increased. With the motion display, the pilot describing functions showed that the crossover frequency increased by 1 rad/sec, and the time delay between input and pilot control response was reduced by 0.15 seconds. They also concluded that the visual display cues were dominant at low frequencies, and that motion display cues were dominant at the higher frequencies.

Bergeron (reference 10) performed an instrumented, moving-base tracking task study in a single-axis mode (roll) and a dual-axis mode (pitch and roll, and

pitch and yaw). With the relatively slow, third order dynamics used, Bergeron found that the addition of motion cues to the visual cues reduced error scores for the dual-axis task, but not for the single-axis task. In other words motion cues were important for the higher workload, dual-axis task, but not for the lower workload, single-axis task. Furthermore, Bergeron found no difference in error scores for dual-axis tracking (pitch and yaw) as the amplitude of the simulator motion was scaled by factors as small as one fourth.

Research related to the effect of motion system configurations on simulations was performed by Ringland, et. al. (reference 11). He ranked simulator motion conditions in the order of their adverse effect upon pilot performance (beginning with the least adverse) as (1) angular motion, (2) angular plus linear motion and (3) no motion (fixed-base).

Miller and Riley (reference 12), investigating a four degree-of-freedom tracking task and using error scores, showed that increasing the task difficulty decreased the amount of acceptable delay. With complete motion cues, the pilot could tolerate longer dead time delays in the dynamics than with a limited amount of motion. This is reasonable, as a dead time delay can be viewed as a phase lag which increases with frequency. Thus increased time delay requires the pilot to generate more lead, which motion cues facilitate.

In summary, research to date indicates that piloted aircraft simulations can be used for training and to obtain valid data for use in the development of aircraft and aircraft systems. Additionally, under many flight conditions, motion cues are needed to produce a valid simulation. Consequently, numerous simulation facilities have the capability for producing motion cues. Because of the relatively large mass to be moved, the frequency response of most motion systems drops off in the vicinity of 6 rad/sec, in contrast to the visual cues which usually have a frequency response which is flat past 20 rad/sec. This paper reports on an experiment designed to investigate the effects of such a mismatch between the visual and motion cueing systems.

The Experiment

Figure 2 shows the compensatory roll tracking task used for the experiment. The pilots were able to perceive the roll error through a visual and a motion simulator, and were requested to maintain level flight in the presence of turbulence during each run. In other words, while sitting in the closed motion simulator with a TV picture in front of them, the pilots attempted to keep the cab and the TV picture at a zero degrees roll angle. Perfect performance was not possible because of turbulence.

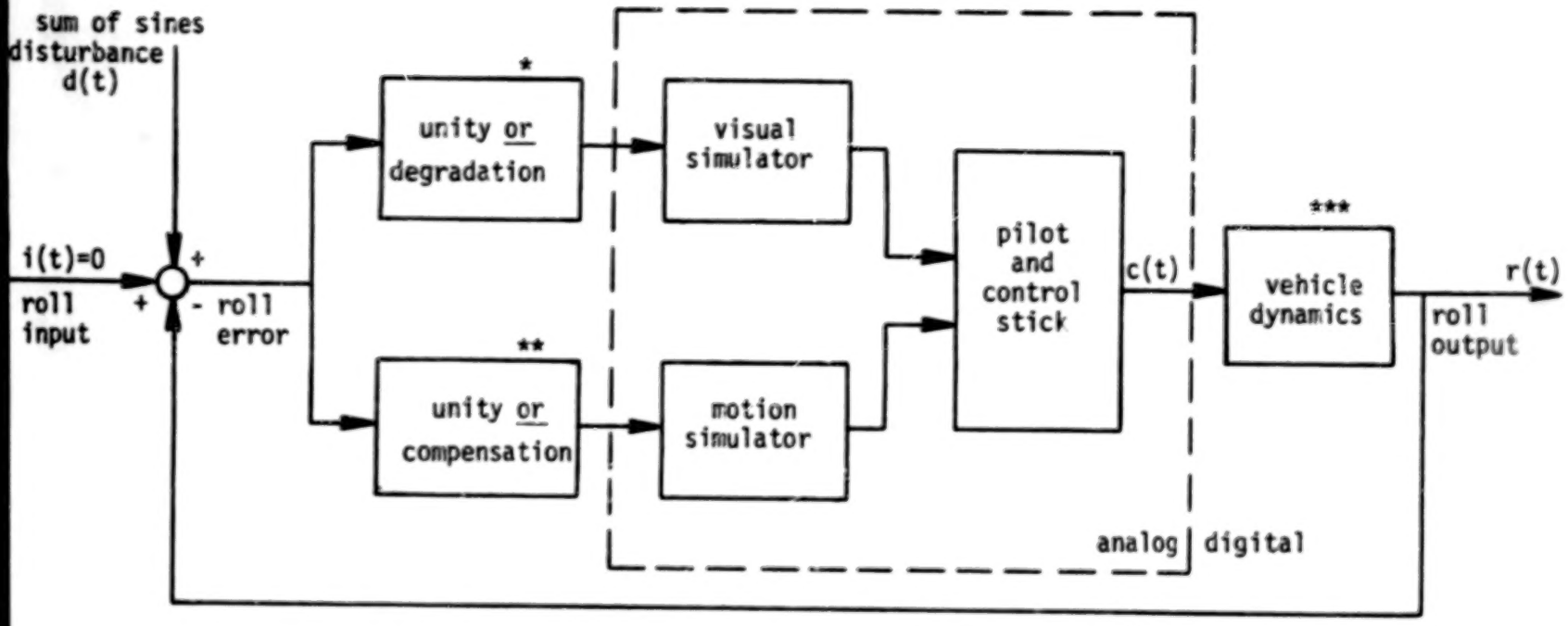
The dynamics of the visual and motion simulators were not identical, producing a slight mismatch between the information presented to the pilot through these two displays of roll error. In order to measure the effects of such a mismatch (or conflict of cues) on pilot performance, the visual and motion dunamics were systematically compensated or degraded (see Figure 2) to create four display combinations (see Figure 3):

- Case A - normal visual and motion displays, consequently a conflict of cues
- Case B - visual display degraded to match the motion display, no conflict of cues
- Case C - motion display compensated to match the visual display, no conflict of cues
- Case D - visual display degraded to match uncompensated motion display, and motion display compensated to match undegraded visual display, producing a slight conflict of cues (opposite of Case A)

The dynamics shown in Figure 3 are discussed later in the paper under Description of Equipment.

Two different aircraft roll dynamics were used during the experiment, and the data analyzed separately. The dynamics, described in the next section, were typical of medium transport aircraft.

During the runs the roll error and pilot control output were sampled every .05 seconds. These data were used to calculate pilot quasi-linear describing



*visual degradation: 1/(.21s+1)

**motion compensation: (.21s+1)

***vehicle roll dynamics:

case 1: 8.8/s(.5s+1)

case 2: 37.25/s(.5s+1)

Figure 2: Single-Axis Compensatory Roll Tracking Task

Figure 3

Visual/Motion Roll Display Dynamics

Visual \ Motion	Normal	Compensated
Normal	Case A Visual: 1 Motion: $\frac{1}{.21s+1}$ (normal)	Case C Visual: 1 Motion: 1 (high ω)
Degraded	Case B Visual: $\frac{1}{.21s+1}$ Motion: $\frac{1}{.21s+1}$ (low ω)	Case D Visual: $\frac{1}{.21s+1}$ Motion: 1 (reverse normal)

functions and error scores. At the end of each set of runs pilot opinion ratings were obtained.

The following sections describe the aircraft dynamics, the equipment, the experimental procedures and the analysis techniques used for the experiment. Experimental results are then presented, and conclusions are made based on these results.

The Aircraft Dynamics

The aircraft roll dynamics used in two separate experimental cases were:

$$1)\quad \frac{\phi_a}{\delta} = \frac{17.6\ (0.5)}{s(0.5s + 1)}$$

$$2)\quad \frac{\phi_a}{\delta} = \frac{74.5\ (0.5)}{s(0.5s + 1)}$$

where ϕ_a is the roll angle of the aircraft, δ is the control stick deflection, and s is the Laplace operator. Using the pilot opinion boundries of reference 5, dynamics 1 is in the middle of the "Satisfactory" range, while dynamics 2 is just into the "Unacceptable" range.

Description of Equipment

The experimental hardware consisted of a motion display (motion simulator), visual display (visual simulator), stick controller and digital computer system. The motion simulator was the NASA-Ames Six-Degree-of-Freedom (S.01) simulator described by Fry, Grief and Gerdes (reference 13). The simulator was configured as a single-seat, closed-cockpit enclosure with a television video monitor positioned directly in front of the pilot, and was limited to roll motion for this experiment. The simulator roll angle was limited to $\pm 45^\circ$ of rotation, and the pilot's head was located 0.5 meters above the simulator roll axis.

Simulator transfer functions for the normal and compensated roll motion systems were decermined using a least-squares computational technique operating on the

phase angle versus frequency data. Retaining only the first order terms, these were:

$$\frac{\phi_m}{d} \approx \frac{1}{.21s+1} \qquad \text{(normal)}$$

$$\frac{\phi_m}{d} \approx 1 \qquad \text{(compensated)}$$

where ϕ_m is the roll angle of the motion simulator, d is the roll command and s is the Laplace operator. The measured amplitude ratios and phases of the S.01 for the normal and compensated cases are shown in Table I. The normal transfer function measured for this experiment compares favorably with the results of Fry, et. al., who approximated the transfer function as:

$$\frac{\phi_m}{d} = \frac{1}{.17s+1}$$

The visual display was transmitted via a six-degree-of-freedom, servo-controlled television camera positioned behind a model of a jet tanker over a terrain board. The tanker never rolled relative to inertial space during the experiment. Consequently any rolling of the tanker image on the TV screen was a display of the roll error of the controlled aircraft as diagrammed in Figure 2, and the task was a compensatory roll tracking task. The roll angle limits for the visual servo system were $\pm 100^{\circ}$. The visual scene was limited to move only in roll.

Using least-squares computational techniques for phase data, the transfer function for normal and degraded visual display conditions were determined to be:

$$\frac{\phi_v}{d} \approx 1 \qquad \text{(normal)}$$

$$\frac{\phi_v}{d} \approx \frac{1}{.21s+1} \qquad \text{(degraded)}$$

Table I

	S.01		VFA	
Freq. rad/sec	AR* normal	AR compensated	AR normal	AR degraded
.35	.98	.98	.99	.99
.70	.98	.99	.99	.98
1.05	.97	.99	.99	.97
1.75	.95	1.01	.99	.93
2.62	.92	1.05	.99	.87
3.50	.88	1.09	.99	.80
6.28	.75	1.24	.99	.60
10.47	.58	1.41	1.00	.42
Freq. rad/sec	Phase normal (degrees)	Phase compensated (degrees)	Phase normal (degrees)	Phase degraded (degrees)
.35	-4	+1	0	-5
.70	-8	0	-1	-9
1.05	-12	0	-1	-14
1.75	-20	0	-2	-22
2.62	-28	+1	-3	-32
3.50	-38	-1	-4	-41
6.28	-60	-7	-8	-60
10.47	-89	-23	-13	-79

*AR: Amplitude Ratio

Roll Frequency Response of the S.01 Motion Simulator and the Visual Flight Attachment (VFA) Used for the Experiment.

where ϕ_v is the roll angle of the visual simulator, d is the roll command, and s is the Laplace operator. The measured amplitude ratios and phases for the normal and degraded visual displays are shown in Table I.

Roll axis commands were made by means of lateral movements of the spring-loaded pencil control stick. The maximum allowable stick movement was $\pm 30^{\circ}$. The controller was mounted on a metal box and connected to analog signal lines by means of a flexible cable. The pilot had the option of choosing either his left or right hand to operate the controller.

The computers used to implement the simulation were a medium-size digital and a medium-sized analog computer. The digital computer was equipped with 64K of core memory. The analog computer was the interface between the digital computer and the analog equipment. The only analog components of the system were the visual and motion simulators, the pilot and the stick controller. All other components were implemented as part of the digital computer program.

Experimental Procedure

The experimental subjects were all commercial aircraft pilots with 2,000 to 10,000 hours of flight time. Their experience included single and multi-engine propeller aircraft, single and multi-engine jet aircraft, and helicopters. All had experience with and were currently qualified to fly one or more transport aircraft. Eight pilots participated in the experiment: five flew both dynamics 1 and 2, two flew only dynamics 1, and one flew only dynamics 2.

Once seated in the closed cockpit of the motion simulator, with the TV visual display in front of him, the pilot's task was to maintain zero degrees roll angle in the presence of the sum-of-sines disturbance. There was a ten-second transition phase at the beginning of each run to gradually introduce the disturbance and minimize transient effects on the pilot and simulation equipment. In addition, a fifteen-second warmup period followed the transition phase. The warmup period allowed longer transients to die out and the pilot to become accustomed to the task. The warmup period was then followed by 108 seconds of simulation runtime during which data were taken. The transition phase, warmup period and data-taking period constituted one run.

Each pilot was assigned a particular display case sequence, and the order of presentation for one subject was balanced by the reverse order of another subject to eliminate possible learning effects. During training each subject was presented with his first display case, and would repeat runs for that case until his error scores remained nearly constant and no more than three data points were rejected. The training then continued with the next display case. Data points were rejected if the response power at the disturbance frequency was less than four times the power of the output response at the two remnant frequencies adjacent to the disturbance frequency (see Table II).

Rest periods of at least ten minutes were provided between training sessions. Training sessions ranged from thirty minutes to an hour depending upon the pilot. Total training time for each pilot ranged from two to eight hours, with an average of slightly over four hours.

Data runs were made in groups of six at each display case. A data-taking sequence started with two warmup runs, and was immediately followed by the six data runs. A rest break was taken before another data-taking sequence was made at the next display case. Total elapsed time for the two warmup and six data runs was typically thirty minutes.

Analysis Techniques

The analysis portion of the experiment included calculation of pilot describing functions, pilot performance scores, average results and an analysis of variance, as well as use of two types of pilot ratings.

The method used to calculate describing functions is described by Shirley (reference 14), and is summarized by Appendix A. The disturbance function used in the experiment was a sum-of-sines whose frequencies and amplitudes are given on Table II. The sinusoids were scaled with frequency to approximate turbulence. The maximum amplitude for the sum-of-sines function was 9°, and the RMS value was 4.5°. In addition to the pilot amplitude ratio and phase calculated at the disturbance frequencies, pilot remnant was calculated at the "remnant" frequencies shown on Table II.

Table II

Parameters for Sum-Of-Sines and Remnant Frequencies

k	W_k Input Disturbance frequency (rad/sec)	K_k Individual sinusoid gain	Remnant frequency (rad/sec)
1	.35	1.	.17
2	.70	-1.	.62
3	1.05	.9	.87
4	1.75	.9	1.57
5	2.62	.8	2.09
6	3.49	-.6	3.14
7	6.28	-.4	5.23
8	10.5	.1	7.85
9	-----	----	15.7

Disturbance = $d(n\Delta t) = G \sum_{k=1}^{8} K_k \sin(W_k n\Delta t)$ where G = 2. and Δt = .05 seconds.

Pilot performance scores were computed as the normalized sum of the absolute values of the performance variable over time (integral-absolute, IA), and the normalized sum of the squares of the performance variable over time (integral-squared, IS).

$$IA_x = K \sum_{n=1}^{N} |x(n)|$$

$$IS_x = K \sum_{n=1}^{N} x^2(n)$$

where x refers to the variable being measured (either roll attitude error or control stick position), and K is a constant. Data samples were taken every .05 seconds.

The pilot describing functions and pilot performance scores for each experimental run were stored on magnetic tape in a 200 word data block. The run number, data, time of day, subject code, aircraft dynamics code, display condition code, and analog scale factors were also stored within the same data block. Using this tape, averages and standard deviations of the data for a sequence of runs under the same experimental conditions and pilots were computed. The variables analyzed were the amplitude and phase of the pilot describing functions, the remnant spectrum and pilot performance scores.

A three-dimensional analysis of variance was performed on the pilot describing functions, remnant and error scores with the following dimensions: display case, pilot, and repeated runs. Each measurement of pilot amplitude ratio, phase, and remnant at separate frequencies, plus each pilot rating and performance score was considered an independent measure of pilot performance. Because the same experimental subjects were used for all of the display cases, the three-dimensional analysis used in this experiment is a special case of a two-dimensional analysis with data replication. The number of data runs was determined using an approach described by Kirk (reference 16). Based upon a set of sample runs performed by a test subject, 42 runs were required for dynamics 1, and 36 runs for dynamics 2.

Finally, a detailed investigation of the effects of the experimental display conditions upon pilot performance was conducted by decreasing the display dimension of the analysis of variance to two variables, and performing the variance analysis for different combinations of paired displays (i.e., display case A versus display case B, etc.).

The pilot opinion ratings used were the Cooper-Harper rating (reference 2) and the Hoh rating (reference 15). The Cooper-Harper rating scale has been used in many studies and is well known. The Hoh rating scale is more recent, and was designed in an attempt to obtain more consistent ratings.

Results

The average pilot describing functions for the four display cases are shown in Figures 4 and 5. Figure 4 shows the average of 42 runs for each display case for dynamics 1 (6 runs for each of 7 pilots). Figure 5 shows the average of 6 runs for each display case for dynamics 2 (6 runs for each of 6 pilots). Similarly, Table III shows the average pilot opinions ratings and error scores as a function of display case, and for each of the two aircraft dynamics.

Using data from all the subjects, two-sided F-tests applied to the analysis of variance are used to determine whether significant differences exist between the results for the four display cases. The results of the analysis are presented in Table IV, which lists only those data points for which there is a significant trend at the .02 confidence level.

Conclusions

The following conclusions are made in the context of this experiment. They consequently apply to trained pilots flying a single-axis, roll compensatory tracking task with both visual and motion cues. In the following discussion, "high frequencies" means above 3.5 rad/sec, and "low frequencies" means below 3.5 rad/sec. Conclusions are based on the results summarized in Table IV, and the direction of trends as shown by Figures 4 and 5. See Figure 3 for a summary of the four display cases A, B, C and D.

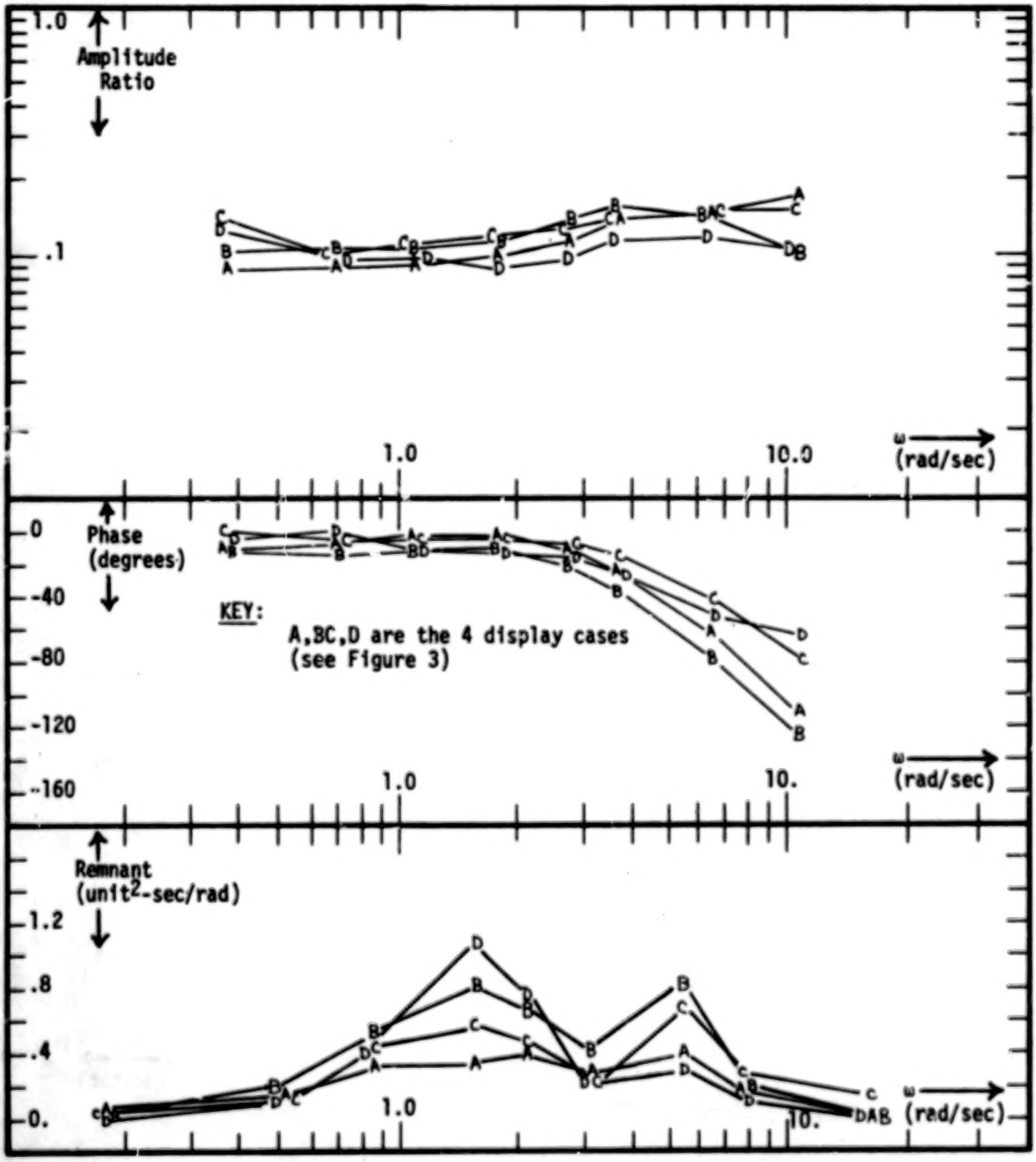


Figure 4: Average Pilot Quasi-Linear Describing Function for Dynamics 1

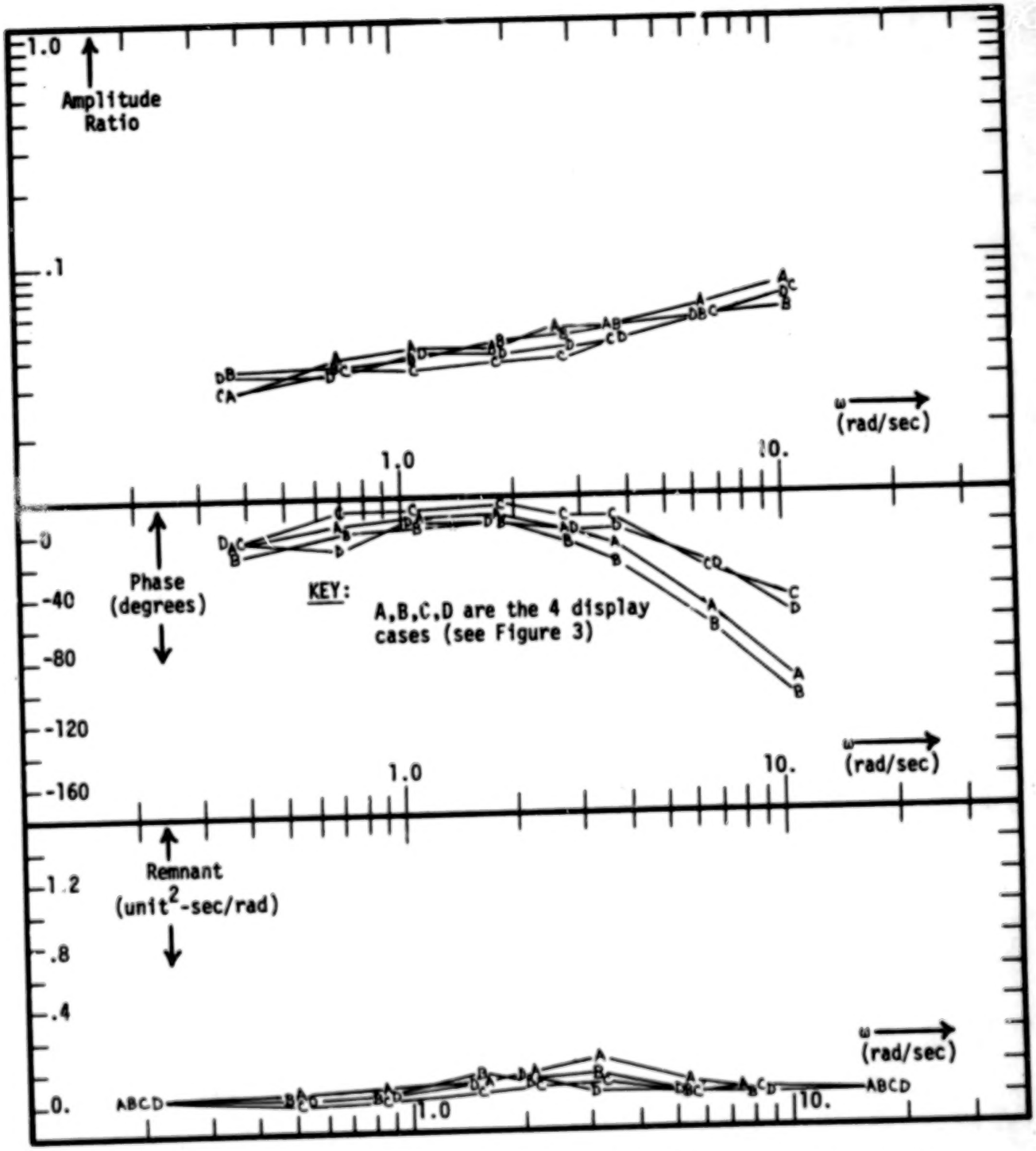


Figure 5: Average Pilot Quasi-Linear Describing Function for Dynamics 2

Table III

Summary of Average Pilot Ratings and Error Scores

	Average Cooper-Harper Pilot Ratings			
	Display Case A	Display Case B	Display Case C	Display Case D
Dynamics 1	4	5	4	5
Dynamics 2	6	5	5	5

	Average Subjective (Hoh) Pilot Ratings			
	Display Case A	Display Case B	Display Case C	Display Case D
Dynamics 1	2.65	2.85	2.55	3.02
Dynamics 2	2.75	2.56	2.72	2.85

	Average Integral Square Error Score			
	Display Case A	Display Case B	Display Case C	Display Case D
Dynamics 1	309	343	297	348
Dynamics 2	369	361	316	328

	Average Integral Absolute Error Score			
	Display Case A	Display Case B	Display Case C	Display Case D
Dynamics 1	64	68	63	68
Dynamics 2	70	68	64	66

Between Displays **	Dynamics 1: 8.8/s(.5s+1)	Dynamics 2: 37.25/s(.5s+1)
1) A and B	error scores lower at display A remnant lower at display A *less phase lag (freq. 4,5,6) at display A	less phase lag (freq. 7) at display A
2) A and C	less phase lag (freq. 7,8) at display C	less phase lag (freq. 6,7) at display C
3) A and D	less phase lag (freq. 7) at display A	no significant effects
4) B and C	less phase lag (freq. 2,3,5,6) at display C	less phase lag (freq. 6,7) at display C
5) B and D	no significant effects	less phase lag (freq. 5,6,7,8) at display D
6) C and D	less phase lag (freq. 4,5,6) at display C	no significant effects

*frequencies (rad/sec): 1) .35 2) .70 3) 1.05 4) 1.75 5) 2.62 6) 3.49 7) 6.28 8) 10.47

**Display Cases (see figure 3)

	motion normal	motion compensated
visual normal	A	C
visual degraded	B	D

Table IV: Summary of Significant Effects
(at .02 confidence level)

1) The conflict between visual and motion display characterisitics does not affect pilot performance, but the presence of high frequency information in the visual and/or motion displays does significantly affect pilot performance. Case B (no conflict of cues) is not a more effective display than either A or D, yet both display cases A and D have a conflict of cues. In other words, improving either the motion or visual display used in case B provides information the pilot uses, despite the conflict of cues. Furthermore, improving both displays (i.e. using display C) provides still further information the pilot uses, as case C allows the pilot to generate more lead than either case A or D. Thus the more information available to the pilot, the more he uses, despite the conflict of cues generated by display cases A and D.

2) The most sensitive measure of the display differences was the pilot's phases. Error scores, pilot opinion ratings, pilot amplitude ratios and remnant all showed very little, if any, significant changes. Specifically, in the experiment significant effects were found for one remnant (between cases A and B), for one error score (between cases A and B), and for twenty-two phases (see Table IV). It is felt that significant differences would be found for pilot amplitude ratio and overall error scores in a more difficult or complex task, similar to the experiments of Junker and Replogle (reference 8) or Bergeron (reference 10).

3) Pilots use roll motion cues to generate lead at high frequencies. Significantly more lead was generated by pilots with the motion display compensated in case C, than with the uncompensated motion display in case A. This was true despite the fact that for both cases the visual display contained the same high frequency information present in the compensated motion display. This result agrees with references 6 and 9.

4) The usefulness of roll motion cues for generating high frequency lead increases with plant gain. In going from display case B to D for dynamics 1 (gain 8.8) there are no significant effects despite the compensation of

the motion display. For dynamics 2 (gain 37.25), however, going from display case B to D significantly increases the high frequency lead generated by the pilots. The fact that motion cues are more useful at higher plant gains agrees with the results of references 6 and 9.

5) For dynamics 1 (low gain), pilots use visual cues to generate lead at low frequencies. Degrading the visual display (i.e. going from case A to B or from case C to D) leads to significantly less lead being generated by the pilots at 3.5 rad/sec and below. This is true despite the fact that in both cases C and D the motion display contains the same information as the undegraded visual display. The fact that the visual display is most useful to the pilots at frequencies below 3.5 rad/sec agrees with the results of references 6 and 9.

6) The need for visual cues to generate low frequency lead decreases as plant gain increases. Whether going from display case A to B, or from display case C to D, there are significant effects for dynamics 1 (low gain), and almost no significant effects for dynamics 2 (high gain).

In addition to these six conclusions, it is possible to make some general statements based on the visual and motion cues used in the experiment. When a flight simulation has both visual and motion cues, each cue should be made as close to actual flight conditions as is practical, despite the fact that there may be some conflict of cues between sensory modalities. In the experiment, degrading the visual or motion cues to a first order filter at 4.8 rad/sec was sufficient to change pilot performance, but degrading both visual and motion cues had an even more profound effect.

Motion cues in vehicle simulations are used because in some cases they lead to data which are more representative of actual flight data. The reasons for this are that motion cues can both enhance the overall aura of realism of a simulation, and that motion cues provide an additional feedback path by which the pilot can control the vehicle. Pilot-vehicle crossover frequencies are typically placed at 3 to 4 rad/sec (reference 1). Although it

may not be critical to overall task performance, the experiment clearly shows that pilot performance can be changed by visual and/or motion cues at frequencies as high as 10 rad/sec. Thus motion and visual simulator frequency response requirements may have to be extended to 10 rad/sec for some tasks, especially for the rotational axes.

APPENDIX A

Equations Used to Calculate Pilot Describing Functions

The pilot model used for the experiment is the quasi-linear describing function shown in Figure 6 and reference 1. It is used in the context of a single-axis, compensatory, roll tracking task as shown in Figure 2. The sum of sinusoids disturbance, d(t) used to drive the system (as indicated in Figure 2) is digitally calculated as:

$$d(n\Delta t) = G \sum_{k=1}^{8} K_k \sin(\omega_k n\Delta t) \qquad (1)$$

where Δt is .05 seconds, and K_k, G and ω_k are given in Table II. The following characteristics of the disturbance should be noted:

- an exact integer number of cycles of each frequency, ω_k, occur each 36 seconds
- all the sinusoids pass through either 0° or 180° at the start and end of each data taking period
- there is a phase-in period before the data taking period during which the disturbance is gradually introduced
- there is a warmup period after phase-in to ensure that the pilot is in a steady state condition for data taking
- each data run is 108 seconds long (3 times 36 seconds)

During the data taking period the pilot's input and output, e(t) and c(t), are recorded every Δt. A Fourier analysis is then performed at the driving frequencies (i.e. at those frequencies which comprise the disturbance) as follows:

$$A_{ek} = \sum_{n=1}^{N} e(n\Delta t) \sin(\omega_k n\Delta t) \qquad (2)$$

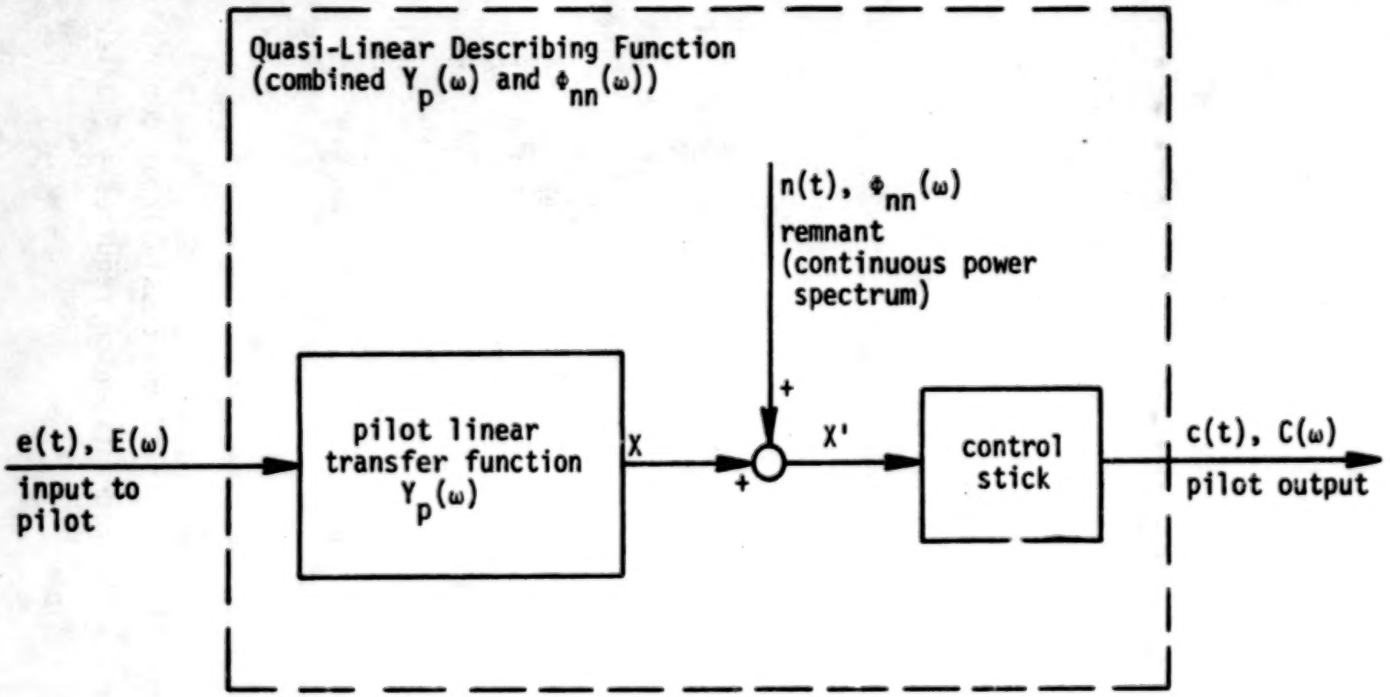


Figure 6: Pilot Quasi-Linear Describing Function

$$B_{ek} = \sum_{n=1}^{N} e(n\Delta t) \cos(\omega_k n\Delta t)$$

$$A_{ck} = \sum_{n=1}^{N} c(n\Delta t) \sin(\omega_k n\Delta t) \qquad \text{(2 Con't.)}$$

$$B_{ck} = \sum_{n=1}^{N} c(n\Delta t) \cos(\omega_k n\Delta t)$$

where Δt and ω_k are given in Table II, and

$$N = \frac{(3 \text{ Periods})\left(36 \frac{\text{seconds}}{\text{period}}\right)}{\left(.05 \frac{\text{seconds}}{\text{sample}}\right)} = 2160 \text{ samples} \qquad (3)$$

The Fourier coefficients are then processed to calculate the pilot's linear transfer function as

$$|Y_p(\omega_k)| = \frac{\left[(A_{ek} A_{ck} + B_{ek} B_{ck})^2 + (A_{ek} B_{ck} - A_{ck} B_{ek})^2\right]^{1/2}}{A_{ck}^2 + B_{ck}^2} \qquad (4)$$

$$\angle Y_k(\omega_k) = \tan^{-1}\left[\frac{A_{ek} B_{ck} - A_{ck} B_{ek}}{A_{ek} A_{ck} + B_{ek} B_{ck}}\right] \qquad (5)$$

Equations 4 and 5 represent the linear part of the quasi-linear describing function. The non-linear part is the remnant, which requires a Fourier analysis at frequencies ω_j as follows:

$$A_{cj} = \sum_{n=1}^{N} c(n\Delta t) \sin(\omega_j n\Delta t) \qquad (6)$$

$$B_{cj} = \sum_{n=1}^{N} c(n\Delta t) \cos(\omega_j n\Delta t) \qquad \text{(6 Con't.)}$$

where N is defined in equation 3, Δt is .05 seconds, and the ω_j are shown in Table II. Note that the ω_j frequencies lie between the driving frequencies, ω_k. The remnant is then calculated as

$$\Phi_{nn}(\omega_j) = K_{nn}(A_{cj}^2 + B_{cj}^2) \qquad (7)$$

where K_{nn} is a scale factor which normalizes the remnant with respect to the input disturbance power, corrects for the run time, and corrects for the bandwidth of the Fourier analysis. K_{nn} is derived as follows: with reference to Table II, the total input power TIP, is given by

$$TIP = 0.5\, G^2 \sum_{k=1}^{8} K_k^2 \quad \text{units}^2/\text{Hz} \qquad (8)$$

The bandwidth of the signals in the digital computer, BW, is determined by the Nyquist frequency as

$$BW = \frac{1}{2\Delta t} \quad \text{Hz} \qquad (9)$$

and therefore the total input power per Hz, TIPH, is given by

$$TIPH = TIP/BW \qquad (10)$$

K_{nn} must include a factor, K_1, to normalize for the input:

$$K_1 = \frac{1}{TIPH} = \frac{BW}{TIP} \qquad (11)$$

Because the A_{cj} and B_{cj} are calculated according to equations 6, a factor of $1/N\Delta t$ is needed to correct for the number of samples taken. This factor occurs in both A_{cj} and B_{cj}, and is squared in equation 7. Hence K_{nn} must contain a factor

$$K_2 = \left(\frac{1}{N\Delta t}\right)^2 \qquad (12)$$

The Fourier analysis represented by equations 6 has an effective bandwidth of $2/N\Delta t$ Hz. For the remnant to be in terms of power/Hz, K_{nn} must include the factor

$$K_3 = \frac{N\Delta t}{2} \qquad (13)$$

Combining the factors

$$K_{nn} = K_1 K_2 K_3 = \left(\frac{BW}{TIP}\right) \left(\frac{1}{N\Delta t}\right)^2 \left(\frac{N\Delta t}{2}\right) \qquad (14)$$

$$K_{nn} = \frac{BW}{TIP} \quad \frac{1}{2N\Delta t} \qquad (15)$$

substituting for BW using equation 9,

$$K_{nn} = \frac{1}{TIP\ 4N(\Delta t)^2} \qquad (16)$$

where TIP is given in equation 8.

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15. Supplementary Notes

16. Abstract

An experiment is performed to determine the effect of a performance mismatch between the visual and motion display systems on a real-time piloted aircraft simulation (usually motion displays exhibit more phase lag than visual displays). Pilots perform a compensatory roll tracking task with dynamics typical of medium jet transports. Between 0 and 10 rad/sec, visual and motion system responses are equivalent to either unity or a first order lag at 4.8 rad/sec. Pilot describing functions and error scores are calculated. Results show that the mismatch between visual and motion display systems has no significant effect; rather, it is the absence of high frequency visual and/or motion cues which significantly affects pilot performance.

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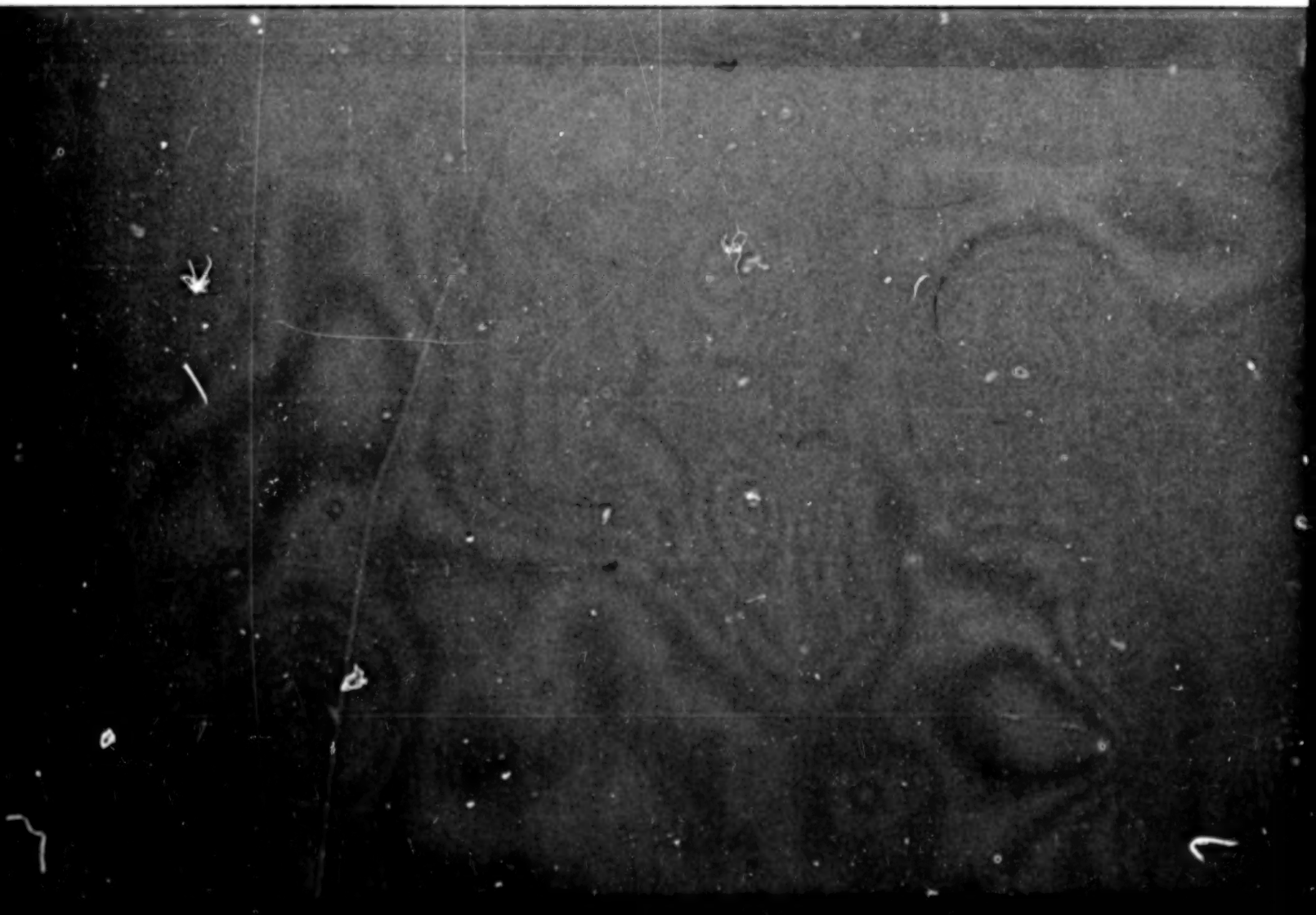

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